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ORBIT TRANSFER VEHICLE ENGINE TECHNOLOGY PROGRAM

COMBUSTOR WALL CONDITION MONITORING - SUBTASK II

TASK E.5

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16. Abstract

Conventional ultrasonics, eddy current, and electromagnetic acoustic transduction (EMAT) technologies were evaluated to determine their capability of measuring wall thickness/wear of individual cooling channels in test specimens simulating conditions in the throat region of an OTVE combustion chamber liner. Quantitative results are presented for the eddy current technology, which was shown to measure up to the optimum 20-mil wall thickness with near single channel resolution. Additional results demonstrate the capability of the conventional ultrasonics and EMAT technologies to detect a thinning or cracked wall. Recommendations for additional eddy current and EMAT development tests are presented.

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OTVE COMBUSTOR WALL CONDITION MONITORING
FINAL REPORT

October 10, 1988

INTRODUCTION

The scope of this effort was to identify and evaluate condition monitoring technologies capable of nondestructively measuring wall thickness and the extent of cooling channel "doghousing" in test specimens emulating conditions which may exist in the throat region of the OTVE main combustion chamber after multiple firings. These measurements can then be correlated to the remaining combustor life, and predict the overhaul schedule and requirement.

SUMMARY

A literature search was performed resulting in thirteen candidate sensor technologies, which were initially evaluated against wall thickness measurement criteria such as thickness range, thickness and channel resolution, accuracy, and the simplicity of the measurement. From these criteria, three technologies-- ultrasonics, eddy currents, and electromagnetic acoustic transduction (EMAT), a noncontacting, couplant-free ultrasonic technique-- were selected for laboratory testing.

Transducers for measuring up to a 20-mil thick wall of copper with single channel resolution, were custom-designed and procured. Transducer fixtures were also designed and fabricated to provide for accurate, automated scans of the test specimens.

Additionally, electromechanical translators were designed and fabricated to move the transducers at selected speeds across the specimens, and to monitor time and amplitude signals. Automated scans were then performed on a curved SSME combustor segment and channeled copper and NARloy Z plates with 20-mil land/channel widths and wall thicknesses simulating OTVE combustor throat conditions.

Conventional ultrasonics easily distinguished between good channels, lands, and cut-through channels, providing a high-contrast amplitude signal. However, in its present configuration, its immersion or liquid couplant requirements inhibit its implementability for space-based applications.

Eddy current techniques were then tested and found to readily resolve a 0-10 mil thick wall thickness, and up to a 20-mil thick wall when not adjacent to thin-walled channels. This technology also provides a high-contrast signal for wall thickness measurements, and has the added feature of not requiring couplants.

The couplant-free ultrasonic EMAT technology was then tested. Results showed that the EMATs could easily resolve signals from a single channel, but that additional data processing algorithms are required to correct for acoustic interference caused by multiple, consecutive channels. Once this is performed, EMAT signal amplitude can be correlated with wall thickness to provide a second couplant-free combustor wall thickness measurement technique.

Continued development of noncontacting measurement technologies such as eddy current and EMAT is essential for enhanced reliability of rocket engine components. Combined with expert systems, these noninferential technologies can provide a fast, fully-automated, in-situ inspection of space-based rocket engine components, minimizing the need for engine disassembly, and reducing turnaround time and life-cycle costs.

The following sections provide technical discussions of the technologies tested and the results obtained.

CONVENTIONAL ULTRASONICS

A two-transducer ultrasonics technique was selected as a candidate measurement technology. This method employed two 10-MHz piezoelectric, focusing, immersion transducers in a pitch-catch arrangement across alternating channel/land sections, as shown in Figure 1. The transducers were oriented 30 degrees from the normal of the specimen, and one focal length (1/2 inch) from the wall surface. One transducer generates an ultrasonic signal which is transmitted through the coupling medium into the wall of the test specimen. The signal is reflected by the channel/wall interface of the test specimen, back into the coupling medium, where it is detected by the second transducer. Wall thickness can then be determined from amplitude measurements of the reflected signals.

Figure 2 shows the experimental results. When the ultrasonic signal is incident on a good cooling channel, the

signal is reflected by the back wall of the channel and easily detected, as shown by the seven good channels and the seven large peaks. When the signal is incident on a doghoused or broken-through channel (fourth channel from the left), the signal is not reflected, and therefore no signal is received by the second transducer. These results show that ultrasonic technique provides a high-contrast signal for Combustor Wall Condition Monitoring. However, the coupling requirements of the immersion technique make the technique impractical. Another ultrasonic approach, the couplant-free electromagnetic acoustic transduction, which will eliminate this impracticality, is discussed later.

EDDY CURRENT

The use of eddy currents as a nondestructive testing method is frequently used for measuring thickness. It has an advantage over conventional ultrasonics in that it requires no liquid couplants and no contact with the object under inspection.

An eddy current transducer contains a coil of wire through which an AC current is passed, creating an electromagnetic (EM) field. The EM field of the transducer, when brought near a conducting specimen, induces eddy currents in the specimen. These eddy currents produce an EM field opposing that of the transducer. This opposing field induces eddy currents in the pickup coil of the transducer. A measure of thickness is obtained from changes in the eddy current magnitude. Data has been collected with two

different eddy current transducers which were custom designed and fabricated for OTVE Combustor Wall Thickness measurements. One probe is a two-element, differential transducer. The other is a single- element transducer.

The first eddy current transducer has two elements which are separated by approximately one tenth of an inch. The coil of each element generates eddy currents in the test specimen, which in turn, generates eddy currents in each receiver coil. Resistance changes due to channel wall thinning cause eddy current amplitude changes, which provide wall thickness measurements. Each element measures eddy currents at a slightly different location of the test piece. The difference in the intensity of the eddy currents produced by the two elements at a particular location is proportional to the wall thickness at that location. As the transducer scans across alternating channels and lands of the test piece, the difference in the eddy current intensity produced by each transducer element provides a wall thickness measurement. When scanning the channeled test piece, the transducer has maximum wall thickness measurement sensitivity and channel resolution when oriented such that one element is over a channel while the other element is over an adjacent land. A Zetec MIZ-17 eddy current tester with a visual display and chart recorder output was used to make the measurements.

Figure 3 shows a scan performed manually over a curved segment of an SSME Main Combustion Chamber. The results

indicate that the two-element transducer can readily resolve visibly thin-walled cooling channels in the SSME combustor segment, and also suggest that it can detect channels with a near-optimum wall.

Next, a fixture was designed and fabricated to hold the transducer. Scanning was automated with a motorized actuator to produce accurate and repeatable results. The transducer was mounted on a translation stage, and the translation stage was moved by the actuator. This automated test set-up was used to perform tests on a copper test plate and a NARloy Z test plate, both of which had 20-mil channel/land widths, simulating throat conditions in the OTVE Combustor.

Figure 4a shows the result of an automated scan of the copper test plate with cooling channels simulating wall thinning and "doghousing". The channels with a 10-mil thick wall or less are readily resolved, and have a signal strength proportional to remaining wall thickness. The channels with a 20-mil thick wall or greater show no apparent signal when adjacent to thin-walled channels. Figure 4b shows the result of an automated scan of the copper test plate with cooling channels having an optimum 20-mil thick wall, with no thin-walled channels nearby. This figure demonstrates the ability of the two-element transducer to resolve the optimum wall thickness of OTVE Combustor Wall cooling channels. Figure 4c shows a plot of eddy current amplitude vs channel wall thickness for the

combined scans of figures 4a and 4b, covering a 1.5-20 mil thickness range with single channel resolution.

Figure 5 is the result from a test on a 24-channel NARloy Z test plate with three channels simulating wall thinning. The three thin-walled channels are easily resolved and have good correlation between signal strength and wall thickness. Again, the large amplitude signal caused by the nearby thin wall overpowers the small amplitude signals from the optimum-wall channels. To date, the two-element transducer has demonstrated the ability to: 1) resolve near-optimum-wall cooling channels which are not adjacent to cooling channels having a wall thickness of 10 mils or less; 2) detect and quantify wall thickness of isolated thinned channel walls.

A second transducer, with a single element, was then tried to determine its thickness measurement and channel resolution capability. This transducer induces eddy currents in a test specimen which are proportional to wall thickness, similar to the two-element transducer technique. As the transducer scans the surface of a test specimen, the amplitude of the eddy currents, again, change with the wall thickness. Use of this transducer has an advantage since it eliminates the necessity of precisely orienting multiple transducer elements with respect to the cooling channels.

To improve the signal strength and channel resolution in the data, data collection was automated through an IEEE-488 computer interface. Data was collected through the

interface from a Tektronix 7D20 digitizer and stored onto computer disks. Once on disks, data from several scans can be added together to increase signal amplitude and to average out noise, thereby enhancing the signal-to-noise ratio. The digitizer also reacts much faster to changes in signal than conventional chart recorders. The signals from the optimum-wall channels, shown in Figure 6, were not detected by a chart recorder, which was simultaneously recording the data.

Figure 6 shows the results of three superposed scans of the NARloy Z test plate, using the single-element transducer. Results indicate that the single-coil transducer can readily locate thin-walls of 5.8 and 10.5 mils, as well as some of the neighboring, but not adjacent, optimum-wall channels. The figure shows the two thin channels and 5 of 11 of the optimum-wall channels, as shown by the solid lines. Undetected channels caused by a nearby thin wall are shown by dotted lines.

These results show that both the single and the two-element eddy current transducers can easily resolve up to a 10-mil thick wall of copper or NARloy Z. Wall thicknesses greater than 10 mils and approaching the 20-mil optimum, produce much weaker but measurable signals, but are undetectable when near thinner-walled channels which produce large-amplitude signals. Thus, the eddy current sensors have been found to be capable of: 1) locating near-nominal channels if remote from thin-wall channels; 2) locating thin

wall channels and; 3) quantifying the wall thickness of individual thin wall channels. These results also provide a high-contrast signal for OTVE Combustor Wall Condition Monitoring, and has the advantage of being couplant-free.

EMAT

It was shown that a two-transducer ultrasonic technique could produce a high-contrast signal for wall condition monitoring, but that immersion might inhibit its implementation. A recently-invented ultrasonic approach uses electromagnetic acoustic transduction (EMAT). The EMATs transmit and receive acoustic waves in a conductor without the use of liquid couplants.

An EMAT consists of a periodic array of permanent magnets wrapped with wire coils, as shown in Figure 7. When placed near a conducting surface, current in the coils induce eddy currents in the conductor. The magnetic field produced by the permanent magnets exerts a Lorentz force on the eddy currents, creating an elastic disturbance in the metal lattice. By periodically pulsing the current in the coils, the elastic disturbances become acoustic waves. The acoustic waves are received by a second EMAT by the opposite process. The acoustic wave in the field of the receiver EMAT coil induces eddy currents in the pick-up coil, and the amplitude of these eddy currents is a measure of wall thickness. The wall thickness determines how much of the wave is reflected. A thick wall will reflect less of the wave than a thin wall. Therefore, the amplitude of the

reflected wave indicates the channel wall thickness. For a sufficiently thick wall, the wave will not be reflected at all.

An Electromagnetic Acoustic Transducer system was custom-designed and fabricated by Innovative Sciences, Incorporated (ISI) specifically for OTVE Combustor Wall Condition Monitoring. Several bread board EMATs were initially constructed by ISI personnel, and they determined that the optimum EMATs for wall thickness measurements are EMATs which produce horizontally polarized shear waves (SH waves). For these SH waves, the motion of the particles producing the wave is perpendicular to the direction in which the wave travels. Figures 8 and 9 show the setup and results, respectively, of a preliminary test performed by ISI personnel when designing the EMATs. The transmitting and receiving EMATs were separated by a distance of 38 mm on a 20-mil thick copper plate with a single 10-mil thick wall between them. The transmitter sends a polarized shear wave horizontally towards the receiver. The receiver senses the wave as it passes underneath, and the amplitude of this initial wave is recorded.

In Figure 9, A is the first wave received directly from the transmitter. B is the reflection from the end of the test plate beyond the receiver. As this reflected wave travels back toward the transmitter, some of the wave is backscattered by the 10-mil channel, producing signal C. Finally, D is the reflection of the backscattered wave from

the end of the plate. Signal D shows an amplitude decrease of nearly 50% of the incident wave caused by reflection backscatter from the single channel, indicating that the amplitude of these reflections can be used to measure combustor wall thickness.

The system was initially tested at Rocketdyne on the copper plate used in earlier eddy current tests. Tests on this plate showed strong signals from the transmitted wave as well as reflected signals from the edges of the plate (Figure 10), confirming results obtained during EMAT fabrication. The transmitted signal is greatly attenuated when the thin-wall channel of the plate is placed between the transmitter and the receiver (Figure 11), demonstrating that the EMAT system can detect thin-wall channels.

The EMAT system successfully identified thin cooling channels on a segment of a curved SSME Main Combustion Chamber. Figure 12 shows the test setup, and Figure 13 shows the signals when the EMAT transmitter and receiver are separated by 30 mm. The first signal (A) is from the acoustic wave traveling directly from the transmitter to the receiver. The second signal (B) is the reflection of thin-walled channels 25 mm away from the receiver. This demonstrates the EMAT's ability to detect wall thinning on a curved surface.

Computer programs were written which completely automated data acquisition and analysis through an IEEE interface. Multiple EMAT signals were averaged by a

tektronix 7D20 digitizer to improve the signal-to-noise ratio, then automatically transferred to computer disks for analysis of signal amplitudes and arrival times. The files were then transferred to spreadsheet programs for more detailed analyses and display.

Using this method, a test was run to try to resolve individual signal reflections from two consecutive thin-walled channels in the copper test specimen. The transducers were positioned with a one-inch separation on the copper test specimen (Figure 14). Signals from the EMATs were sent to the Tektronix 7D20 digitizer, and transferred to computer files for analysis and display.

Figure 15 shows the signal produced for the EMAT configuration of Figure 14. The solid lines at 31.6 usec. and 38.2 usec. represent the arrival times of signals reflected from the edge of the plate nearest the channels. The four dotted lines at 29.2 usec., 30.4 usec., 35.8 usec., and 37.0 usec. indicate the predicted arrival times for reflections from the two thin-walled channels near the edge of the plate, but the experimental signals are not distinguishable in this single test.

One factor limiting channel resolution in the previous test involves transducer ringing. Upon excitation of the EMAT transducer, as in the case of conventional piezoelectric ultrasonic transducers, the transducers have characteristic rise and decay times associated with them. These cause multiple-peak signals, or ringing, as opposed to

single signal spikes, decreasing channel resolution. A second resolution-limiting factor involves constructive and destructive acoustic interference. Phases and amplitudes of acoustic waves reflected from multiple channels with different wall thicknesses, and reflections from the end of the plate, can combine constructively to produce a large signal, or they can combine destructively to produce little or no signal. It should be noted that in the actual case of the circular wall and periodic array of channels in an optimum combustor, there would probably be no appreciable signal from acoustic waves reflected from the channels, reducing the effects of acoustic interference. Signals will appear and increase in amplitude only as channels begin and continue to erode.

To assess the effects of transducer ringing and acoustic interference, a different test was devised. Signal arrival times were obtained at 0.5 mm (20 mils) intervals on two sections of the test plate, one section with the two consecutive channels, and one section without channels (Figure 16). Figures 17 and 18 show the signal arrival times as a function of EMAT position for the 0-channel and 2-channel sections of the plate, respectively.

In Figure 17, the rising slope indicates the increasing arrival time from the reflection off of the near edge of the plate, while the decreasing slope represents the decreasing arrival time as the EMATs approach the farther edge of the

plate. These arrival times show a linear, low-scatter change, as would be expected.

In Figure 18, similar curves appear, but with a high degree of scatter. The solid lines represent the expected arrival time for the reflections from the ends of the plate, while the dotted lines represent the expected arrival times from the reflections off the two channels. These results suggest that additional, more refined data processing algorithms are required which compensate and correct for transducer ringing and acoustic interference in order for the EMATs to adequately resolve signals from consecutive channels. Once this is done, tests can be performed to correlate EMAT signal amplitudes with known combustor wall thickness to complete the EMAT evaluation.

The EMAT system has shown the ability to easily resolve a signal from a single thin-wall channel in a copper plate, as well as multiple thin-wall channels in a curved SSME main combustion chamber. To resolve individual signals from adjacent thin-wall channels, additional data processing algorithms, correcting for acoustic interference and transducer ringing, must be developed. These algorithms will help obtain the single-channel resolution necessary for accurate wall thickness measurements with this noncontacting couplant-free ultrasonic technique.

RECOMMENDED ADDITIONAL TESTING/EVALUATION

EDDY CURRENT: Further tests using eddy currents should be considered to determine if resolution of the optimum-wall

cooling channels can be improved, especially nearby thin-walled channels. Tests with the single-element transducers could include scans at different angles across the channels. Only scans with the transducer moving perpendicular to the channels have been performed thus far. Varying the scan angle to values other than 90 degrees would create a longer scan, making the channels appear wider and possibly easier to resolve. Tests could also be run at different frequencies to maximize channel resolution. Additional tests with the two-element probe should include varying frequency and detector angle while scanning the test specimens to determine if the transducer can resolve both optimum and thin-wall cooling channels which are adjacent.

Additional tests are also necessary to determine how the curvature of the OTVE Combustion Chamber effects the eddy currents and the scan procedure. To best determine the effects of curvature, tests should be performed on the combustion chamber throat of the OTV\ICE. While no absolute wall thicknesses could be determined for this component, the tests would at least provide qualitative and rough quantitative wall thickness information on an actual component. If the ICE component is unavailable, an alternative specimen would be a 1.5-2.0 inch diameter copper tube with channels cut on the outer diameter to various depths. Scans would then be performed on the inside of the tubes to determine if the transducers can resolve cooling channels on this representative curved surface.

EMAT: Additional testing should be performed with the EMAT system using more refined algorithms which correct for acoustic interference and transducer ringing effects present in the data obtained to date. Additionally, tests would be performed on the OTV/ICE combustion chamber component, or perhaps a test calorimeter or channeled copper tube. It should be noted that with the cylindrical chamber test piece, a periodic array of channels and lands would minimize acoustic interference caused by the discontinuities (plate edges) of existing specimens. It is expected that signals from the optimum chamber would be small until the wall of a channel begins to erode, the thinning wall producing a larger reflection signal. Such tests need to be performed to thoroughly evaluate the EMAT technology.

CONCLUSION

Thirteen technologies were evaluated for measuring wall thickness of the OTVE combustion chamber liner wall, and three technologies were selected for laboratory evaluation.

Conventional ultrasonics provided a high-contrast signal, easily distinguishing good channels, cracked channels, and lands. While liquid couplant requirements limit this method's implementability, results suggested a different ultrasonic approach using couplant-free EMATs.

Eddy current techniques were tested and found to resolve up to a 20-mil thick wall over channel/land widths of 20 mils, the optimum OTVE Combustor conditions. Signals from one or two optimum-walled channels adjacent to a thin-

walled channels are not resolvable, but this will not effect the detection of a thinning wall. These results demonstrate that eddy current techniques can provide the necessary wall thickness measurements, and the techniques are couplant-free and fully automatable.

An EMAT system was tested and found to be able to resolve a signal from a single thin-walled channel, but requires that additional signal processing algorithms be developed to correct for acoustic interference from multiple consecutive channels. Amplitude and arrival times will then provide wall thickness and channel locations, respectively.

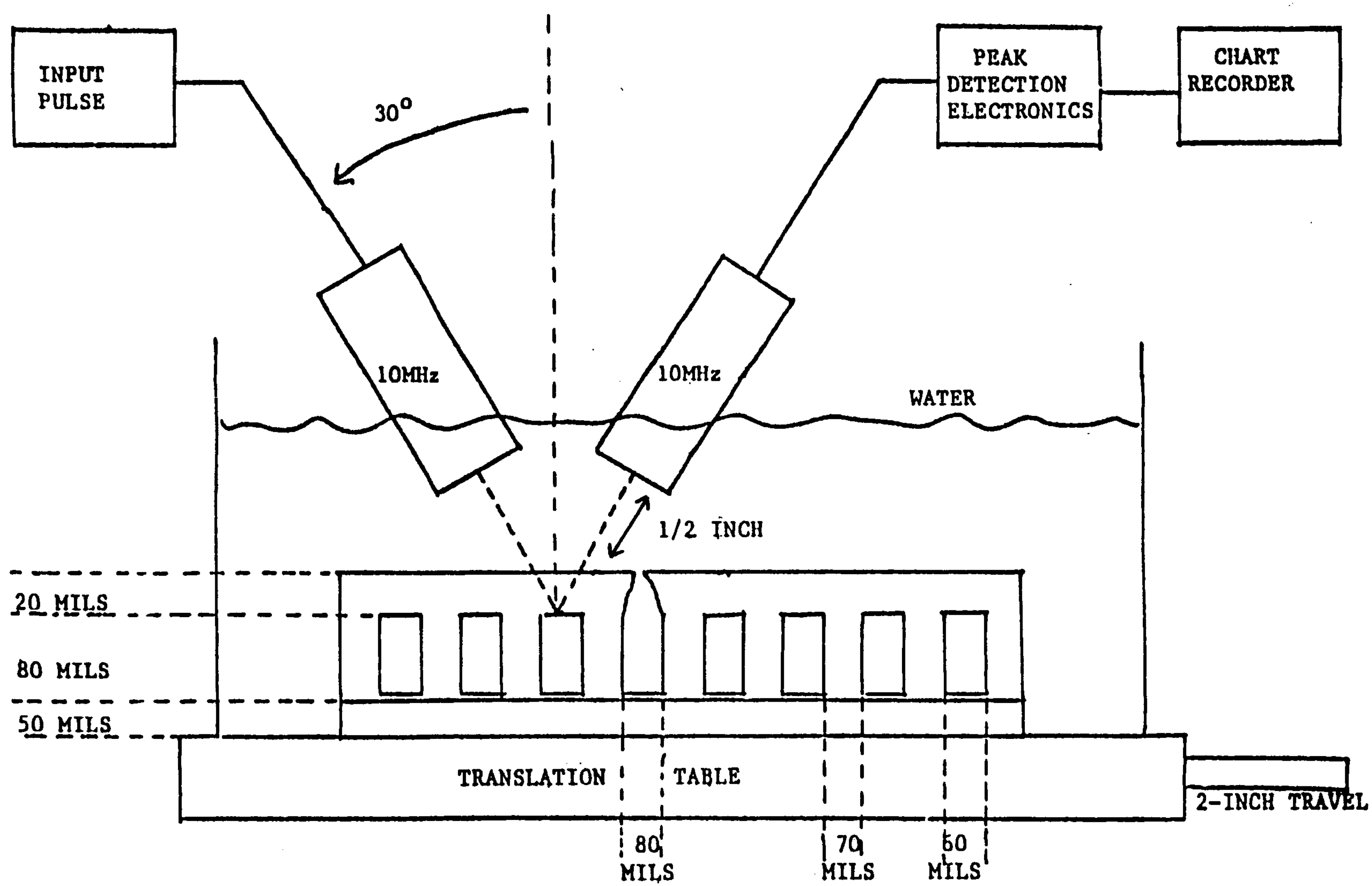

FIGURE 1: Ultrasonic Test Apparatus

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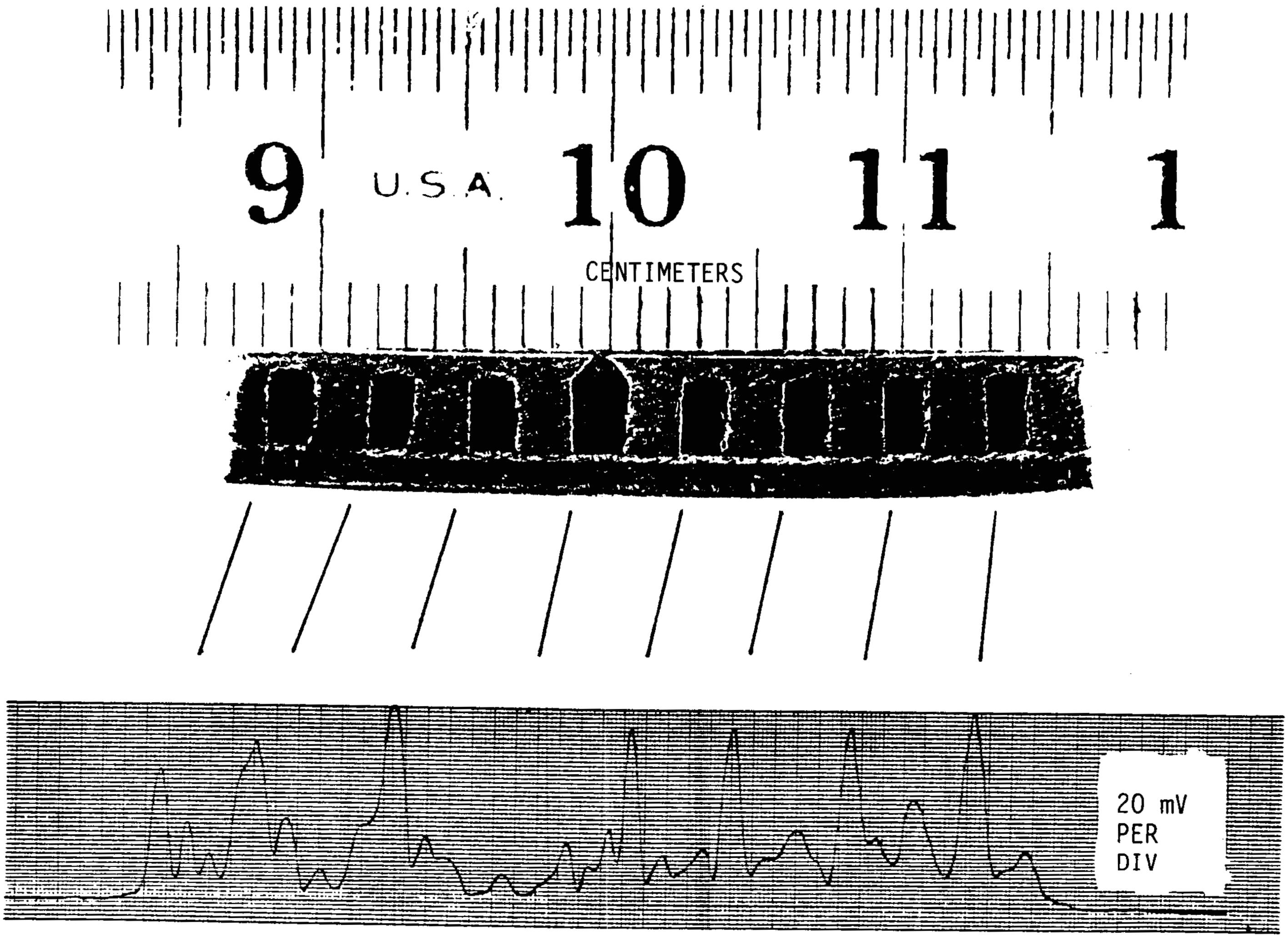

FIGURE 2: ULTRASONIC TEST RESULTS

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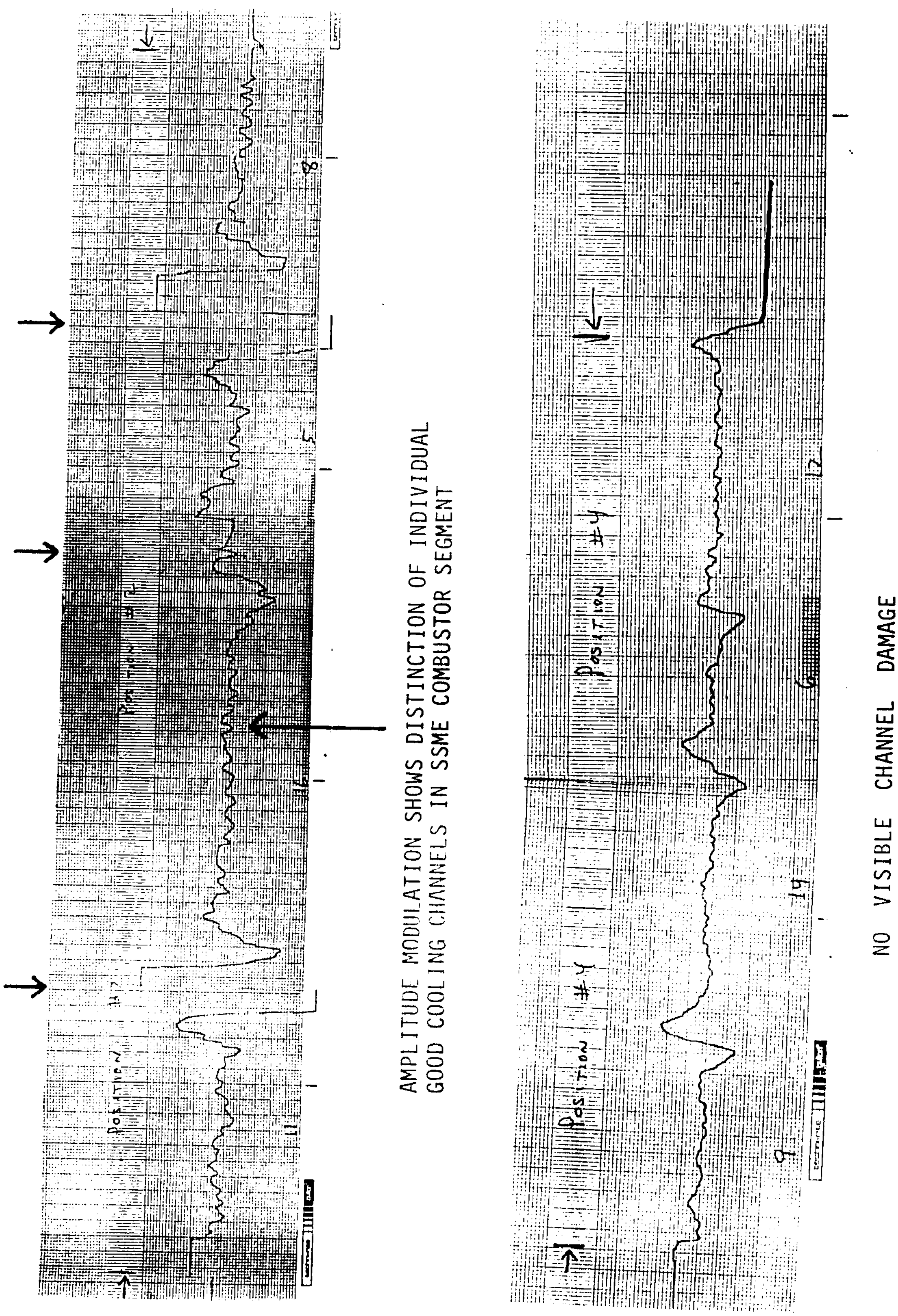


FIGURE 3: EDDY CURRENT SCAN OF SSME COMBUSTOR SEGMENT WITH
DAMAGED AND UNDAMAGED COOLING CHANNELS

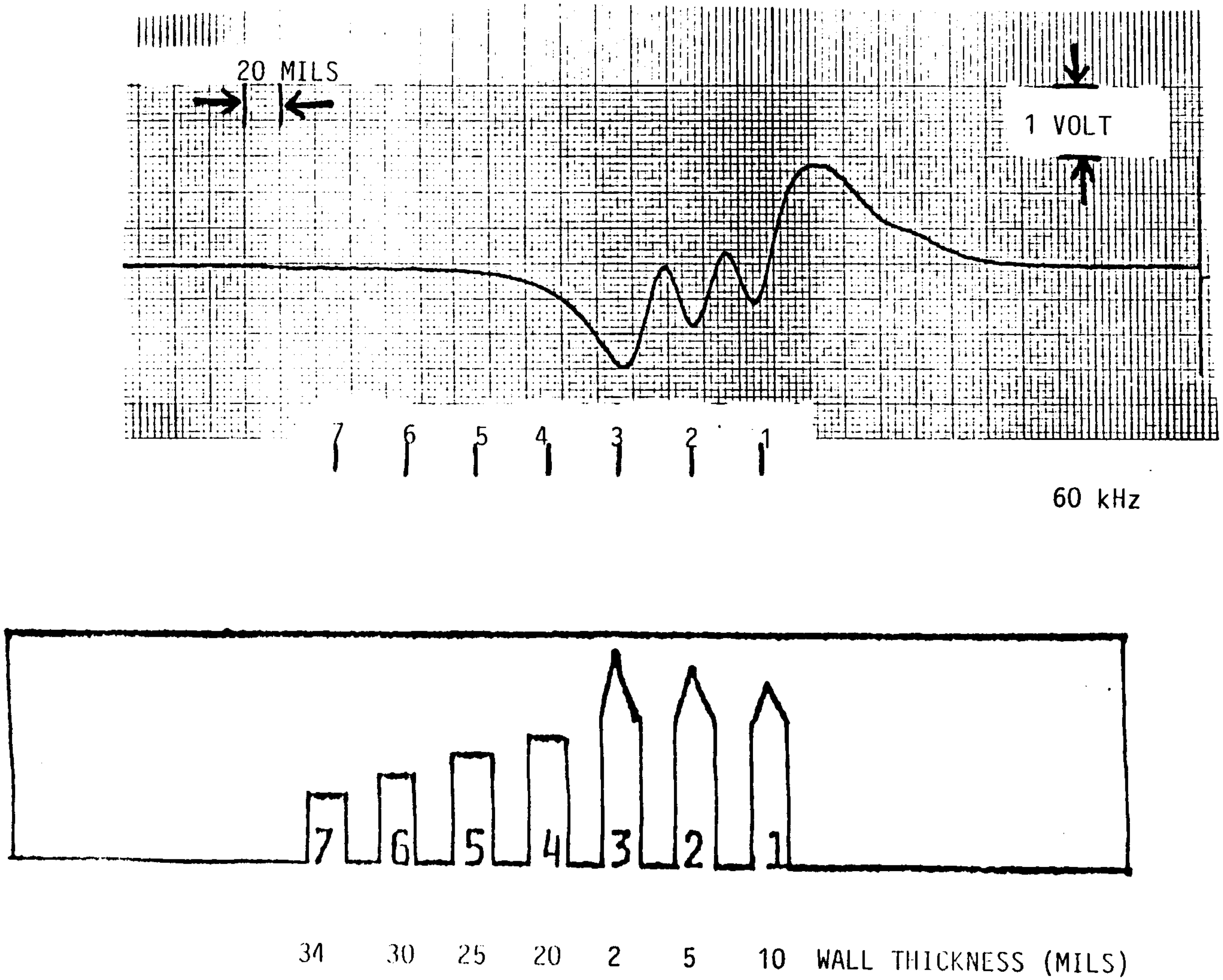
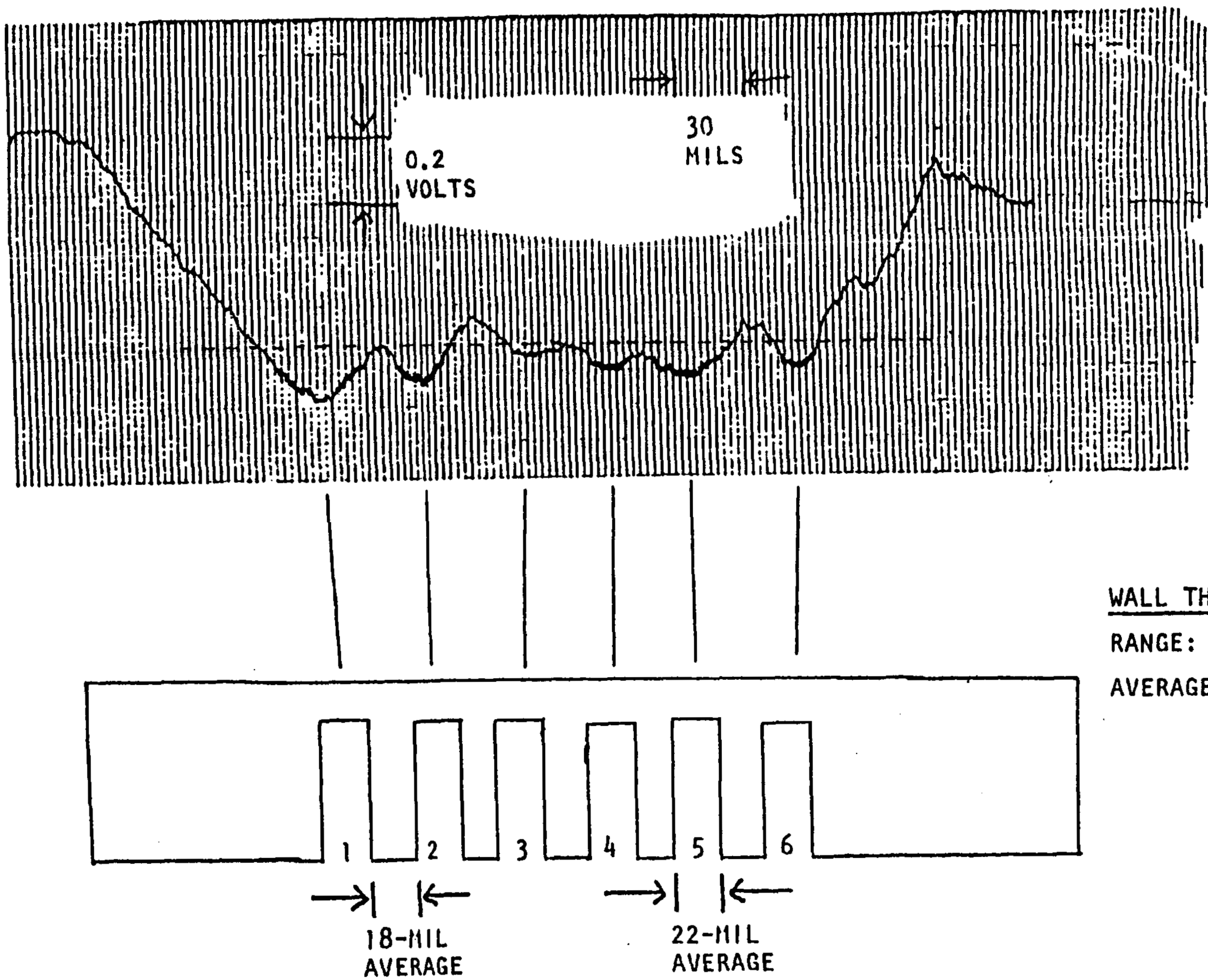


FIGURE 4A: EXPERIMENTAL TRACE OF AN AUTOMATED PITCH/CATCH EDDY CURRENT SCAN OF A COPPER TEST PIECE WITH 20-MIL LAND/CHANNEL WIDTHS

FIGURE 4b

EXPERIMENTAL TRACE OF AN AUTOMATED PITCH/CATCH EDDY CURRENT SCAN OF SIX MILL-CUT CHANNELS IN COPPER

(DOTTED LINE REPRESENTS A ZERO-AMPLITUDE REFERENCE)



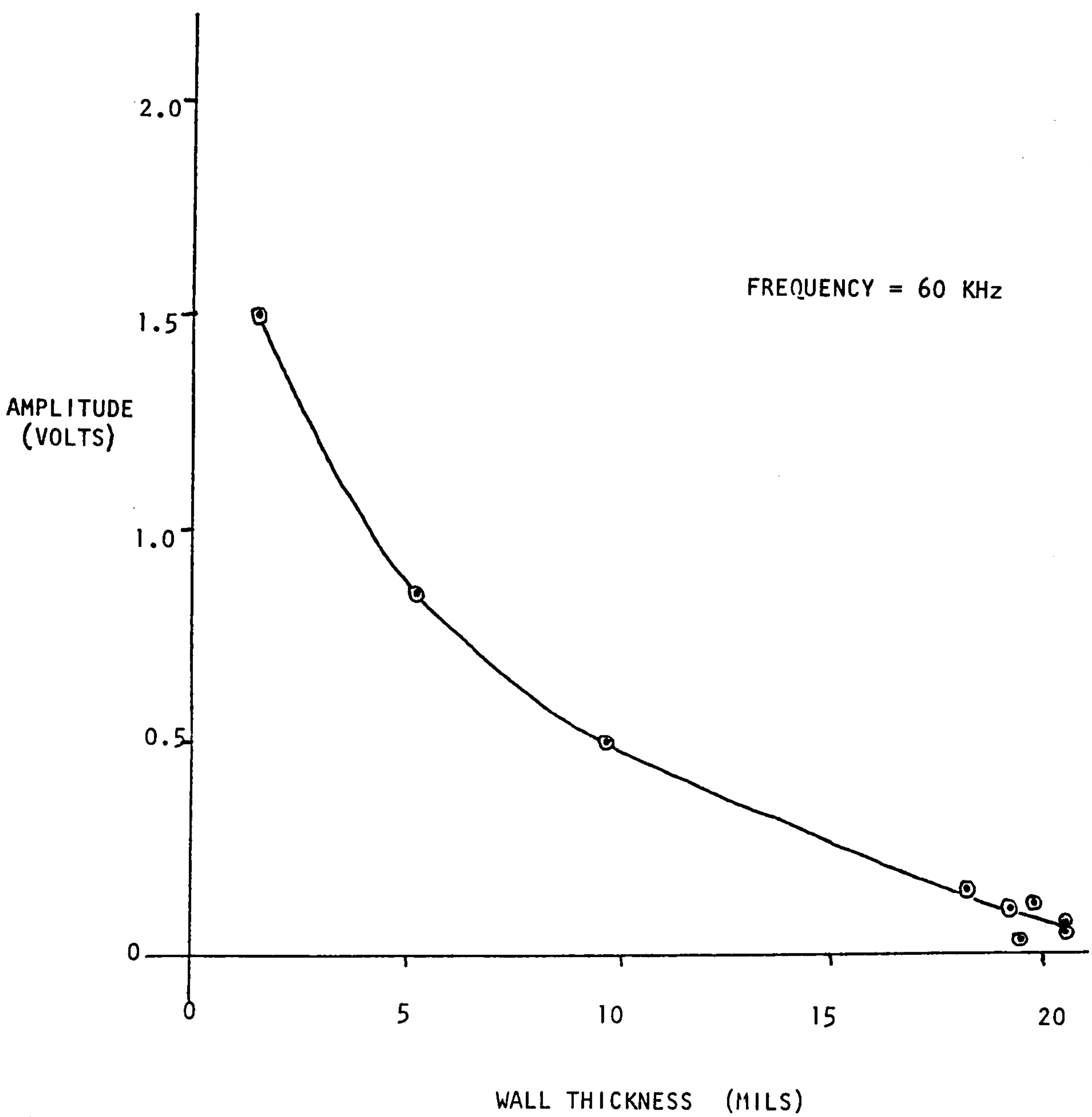
WALL THICKNESS (MILS)

RANGE: 18.5 - 20.5

AVERAGE: 19.5

FIGURE 4C

AMPLITUDE vs COPPER WALL THICKNESS FOR AUTOMATED PITCH/CATCH EDDY CURRENT SCAN



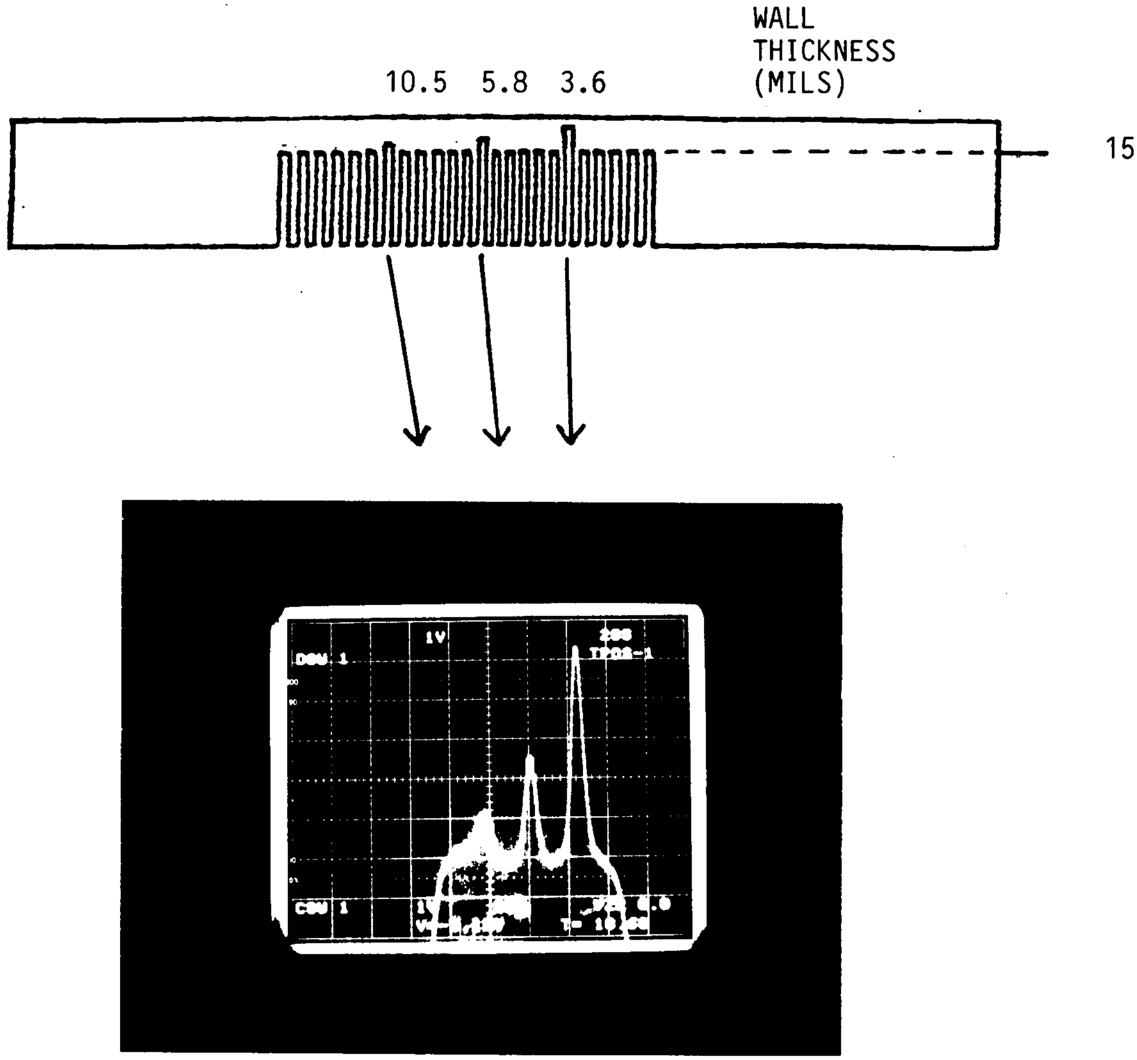


FIGURE 5: DIFFERENTIAL EDDY CURRENT SCAN OF NARLOY Z SPECIMEN SHOWING STRONG SIGNALS FROM THE THREE THIN-WALL CHANNELS

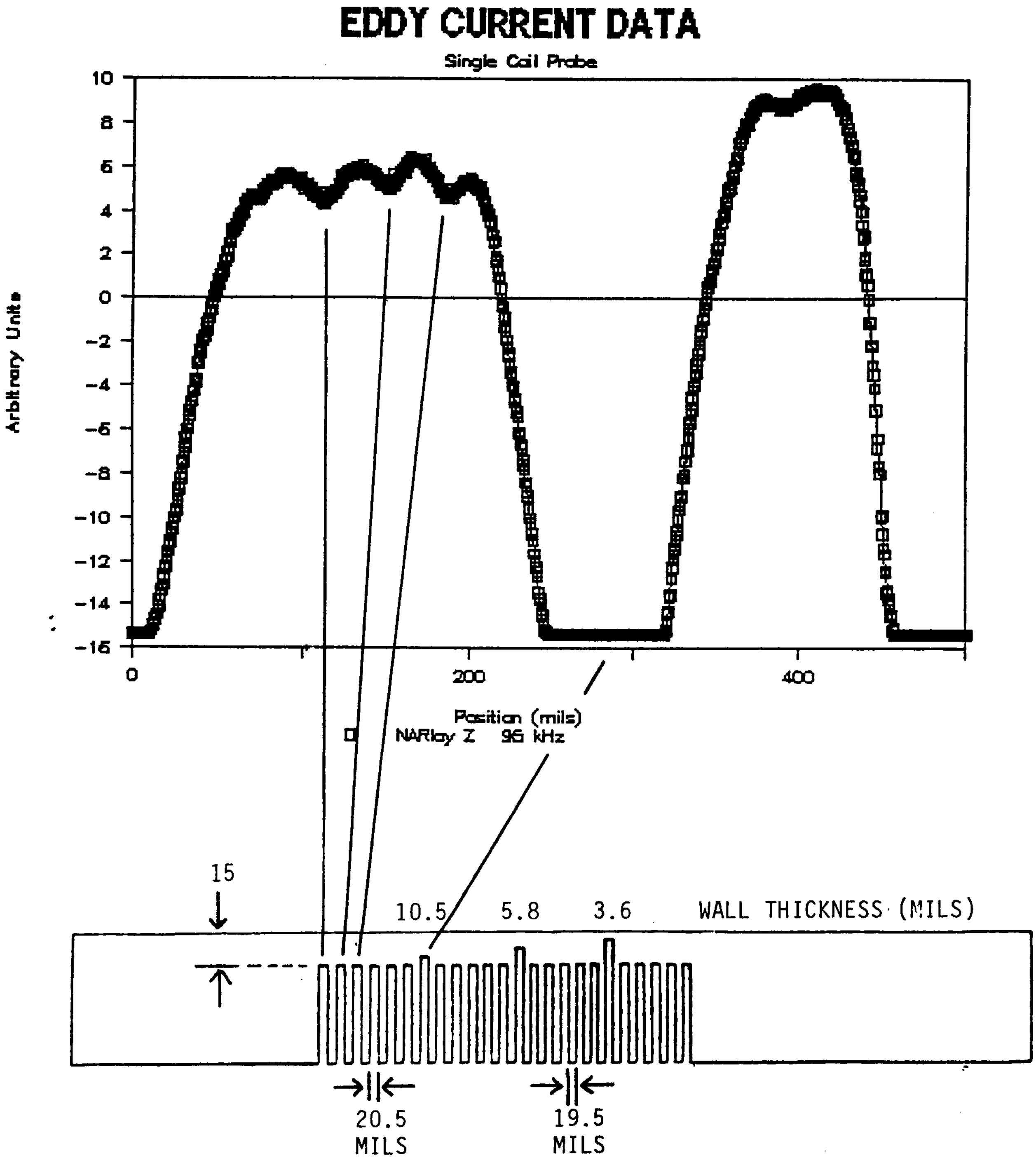
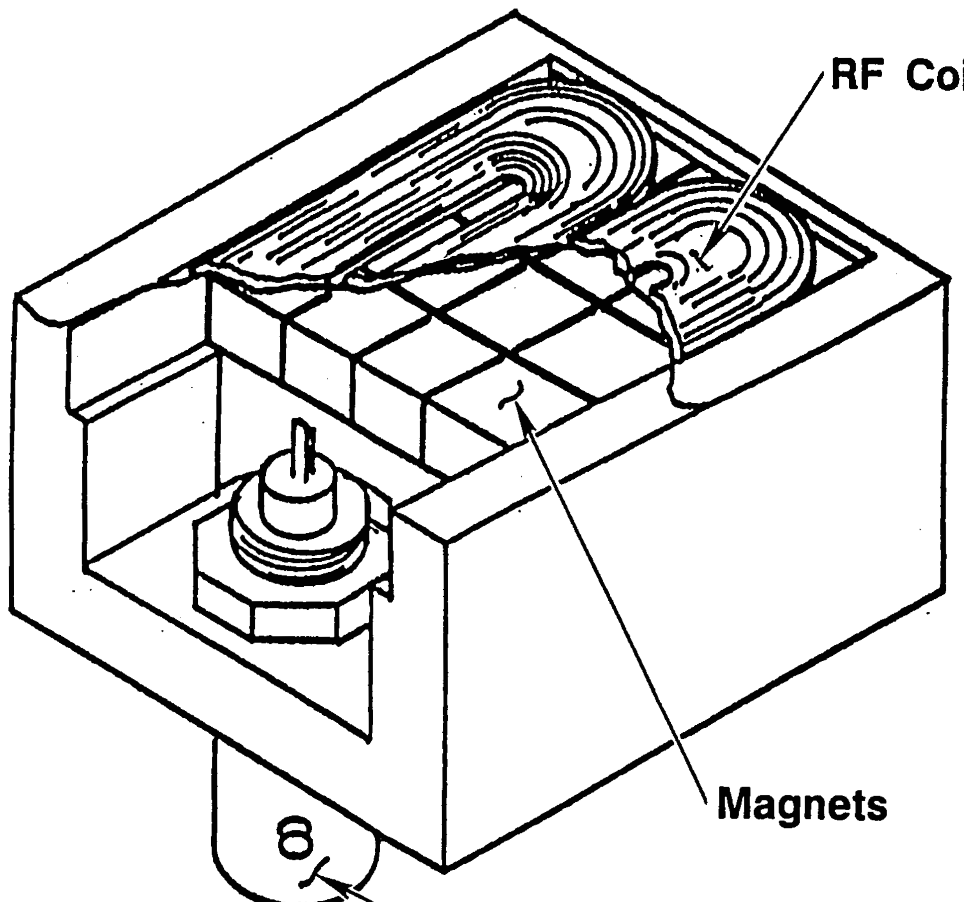


FIGURE 6: EDDY CURRENT SCAN OF A NARLOY Z TEST SPECIMEN
SHOWING OPTIMUM-WALL CHANNELS AS WELL AS THIN-WALL CHANNELS

FIGURE 7

Cutaway View of an EMAT



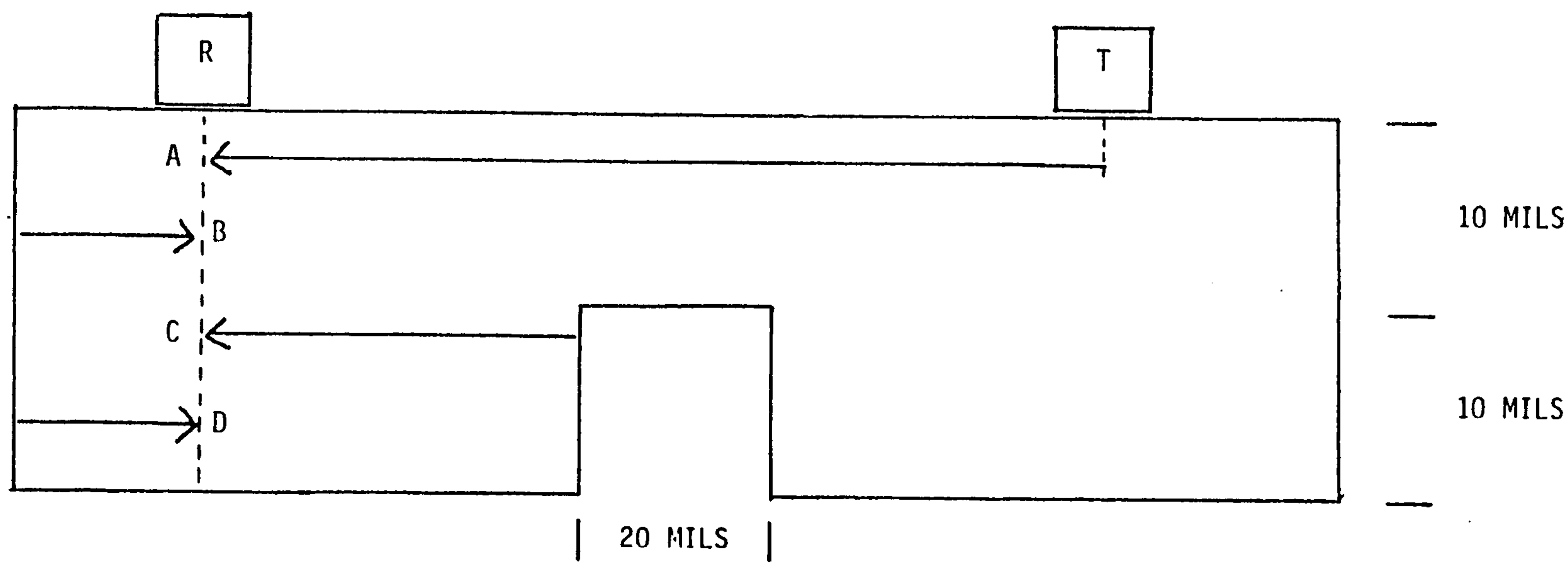


FIGURE 8: SETUP USED DURING THE FABRICATION OF THE TRANSMITTING (T) AND THE RECEIVING (R) EMATS. ARROWS REPRESENT THE FLIGHTS OF THE ACOUSTIC WAVES.

A: DIRECT WAVE FROM T TO R
B: REFLECTION FROM END OF PLATE
C: PARTIAL REFLECTION FROM CHANNEL
D: SECOND REFLECTION FROM END OF PLATE

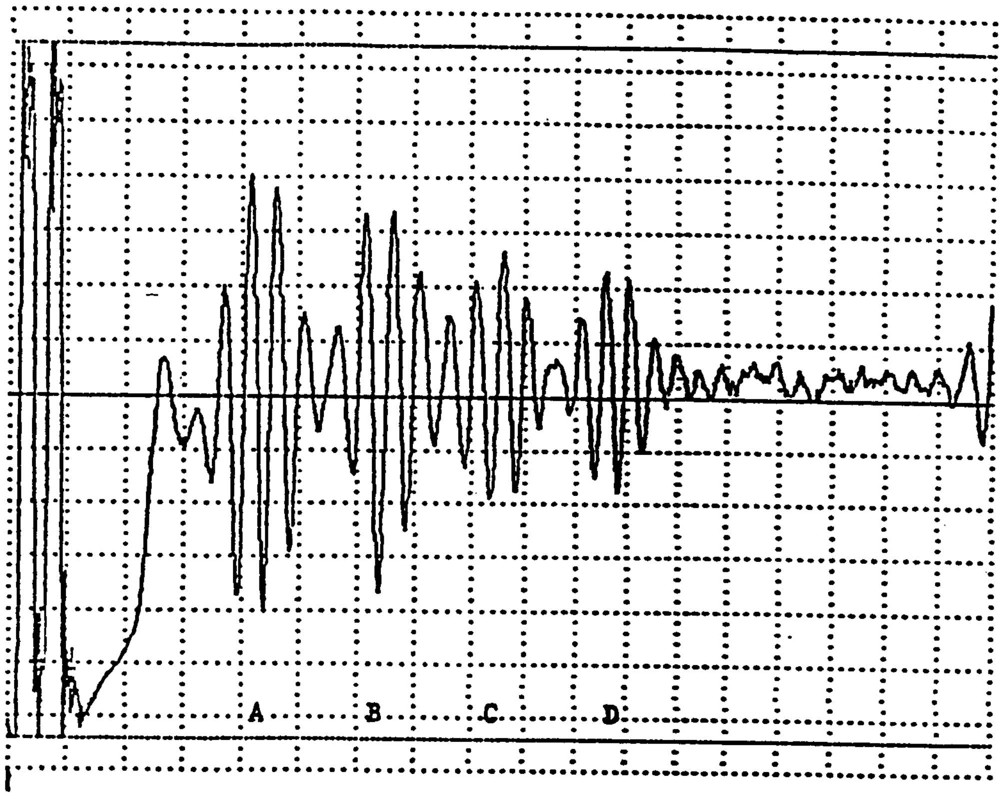
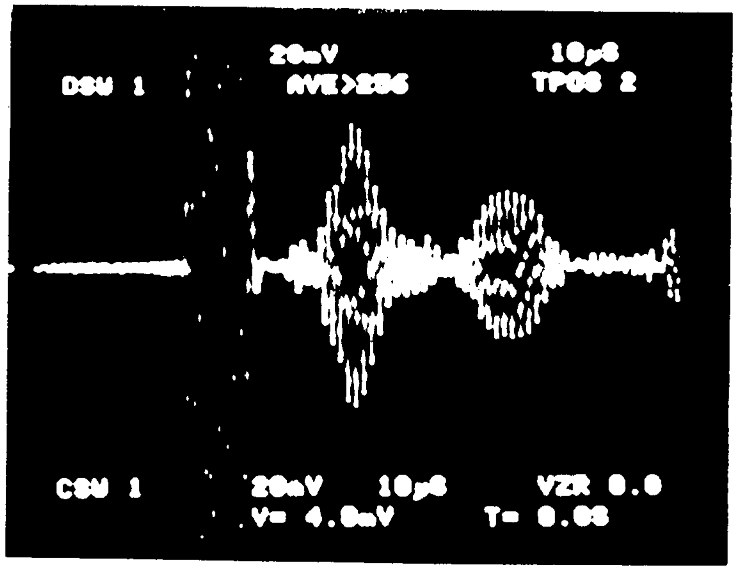


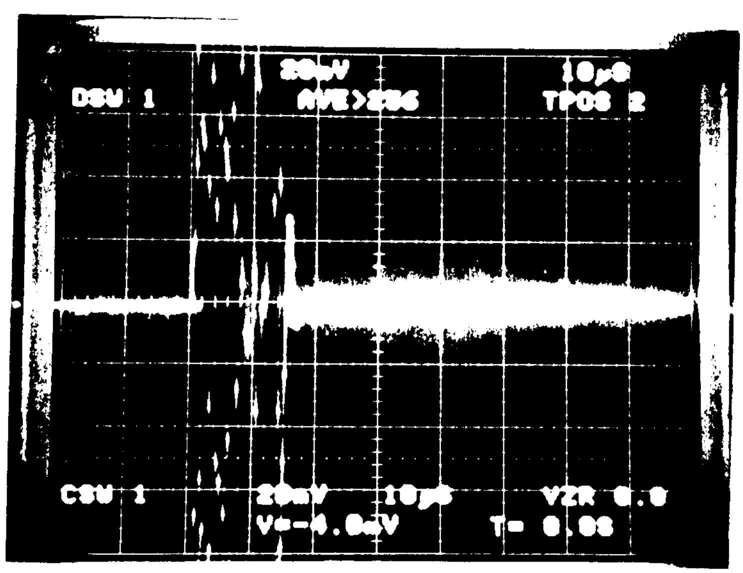
FIGURE 9: EMAT SIGNAL FROM SINGLE CHANNEL IN COPPER PLATE.

A: DIRECT SIGNAL FROM T TO R
B: REFLECTION FROM END OF PLATE
C: PARTIAL REFLECTION FROM CHANNEL
D: SECOND REFLECTION FROM END OF PLATE



A B C

FIGURE 10: NO CHANNELS
A: INCIDENT PULSE (TRIGGER)
B; SIGNAL FROM T TO R
C: REFLECTION FROM END OF PLATE



A B C

FIGURE 11: WITH CHANNELS
A: INCIDENT PULSE (TRIGGERR)
B,C: CRACKED CHANNEL BETWEEN T AND R CAUSES SIGNAL ATTENUATION

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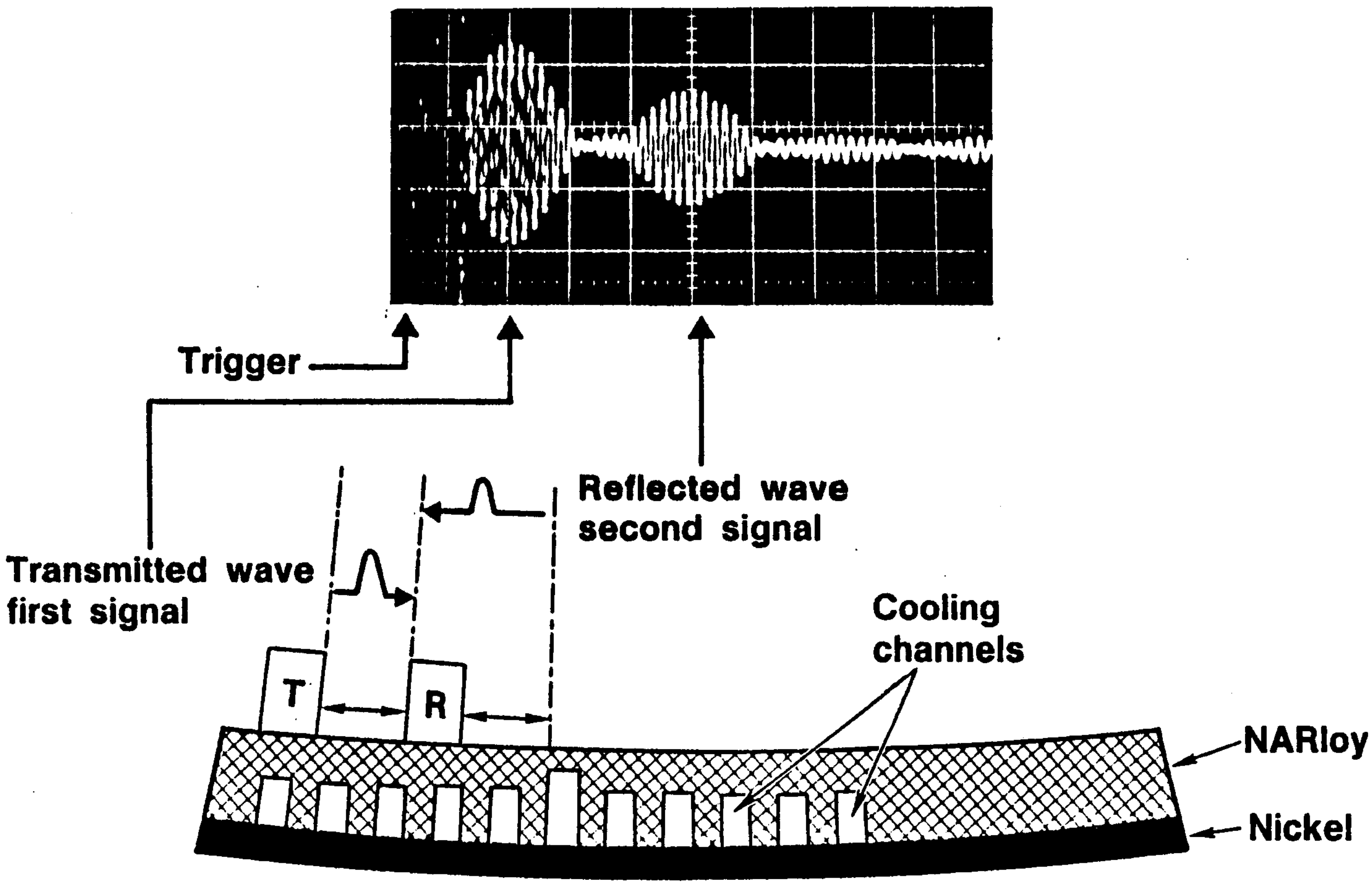
FIGURES 12 & 13

Detection of Thin-Walled Channels in Test Specimen Using EMAT Technology



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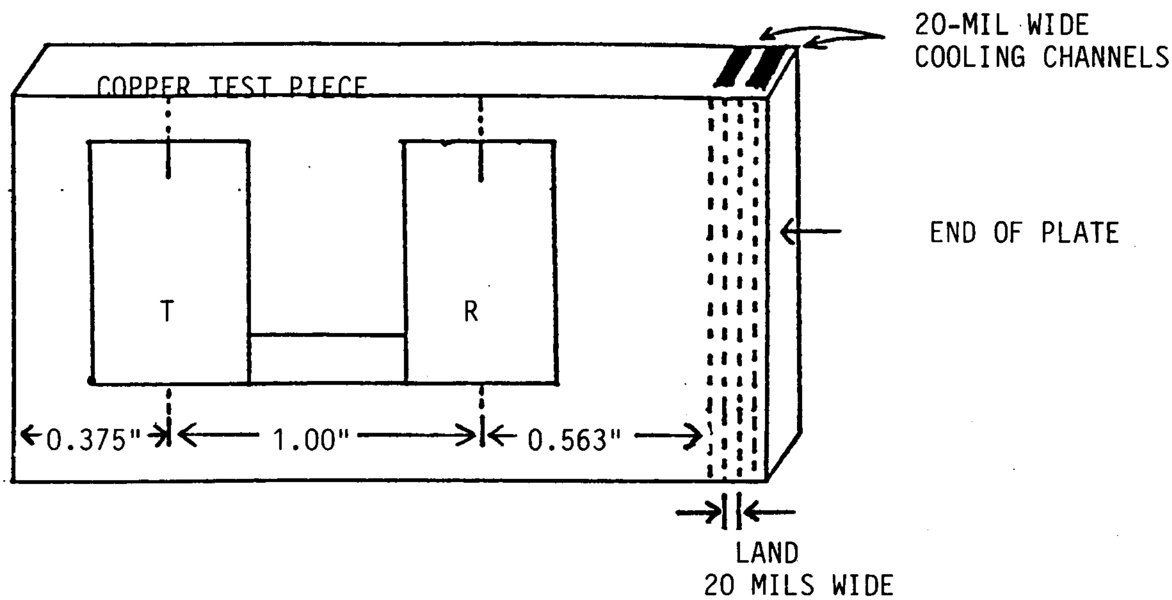

FIGURE 14: ORIENTATION OF EMATS USED TO DETERMINE CONSECUETIVE CHANNEL RESOLUTION CAPABILITY OF THE EMATS.

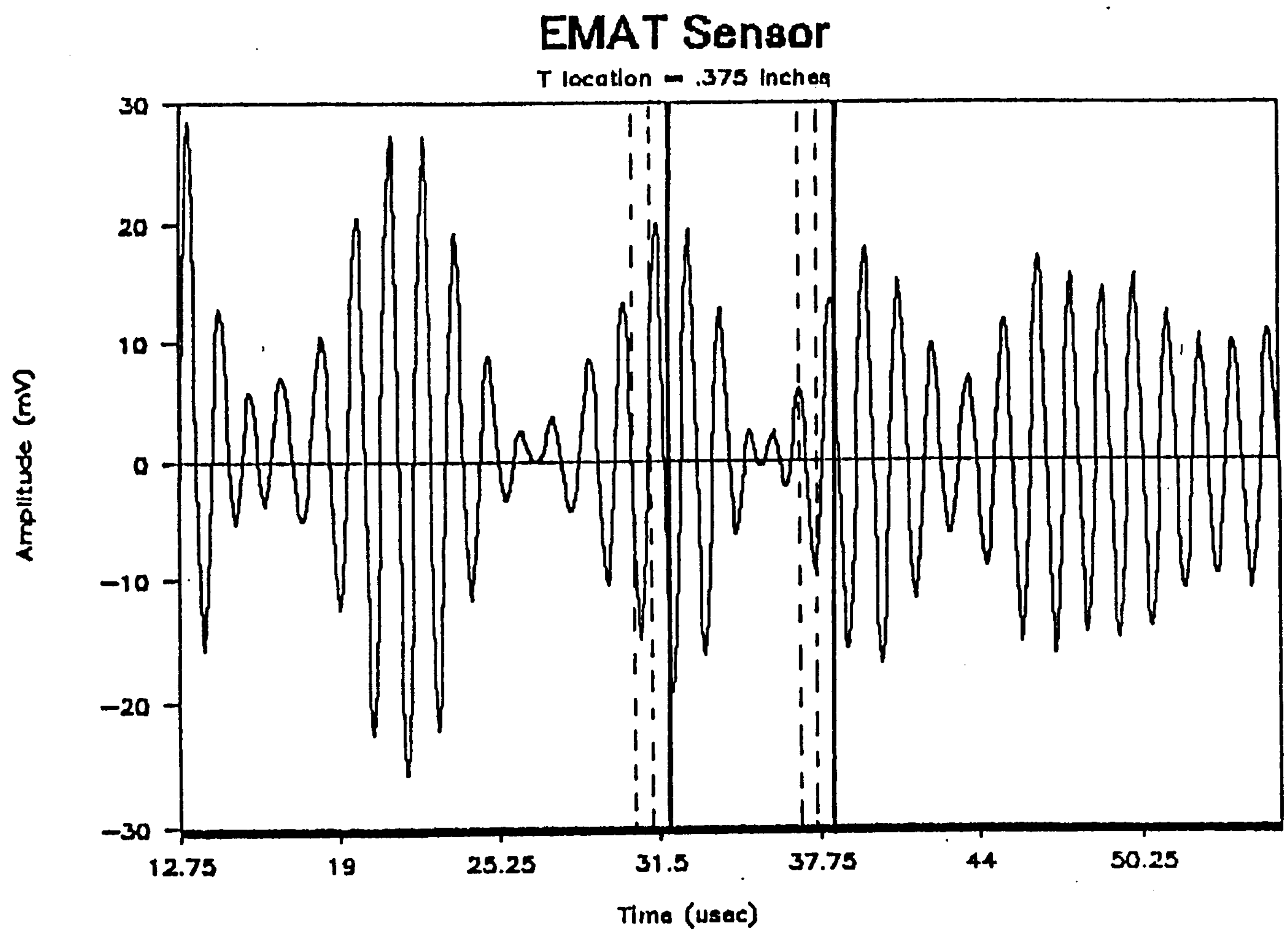

FIGURE 15: EMAT signal. Solid lines at 31.6μS and 38.2μS represent the arrival time of signals from the end of the plate. Dotted lines at 29.2μS, 30.4μS, 35.8μS, and 37.0μS indicate theoretical, yet unresolved, signal arrivals from the two consecutive channels.

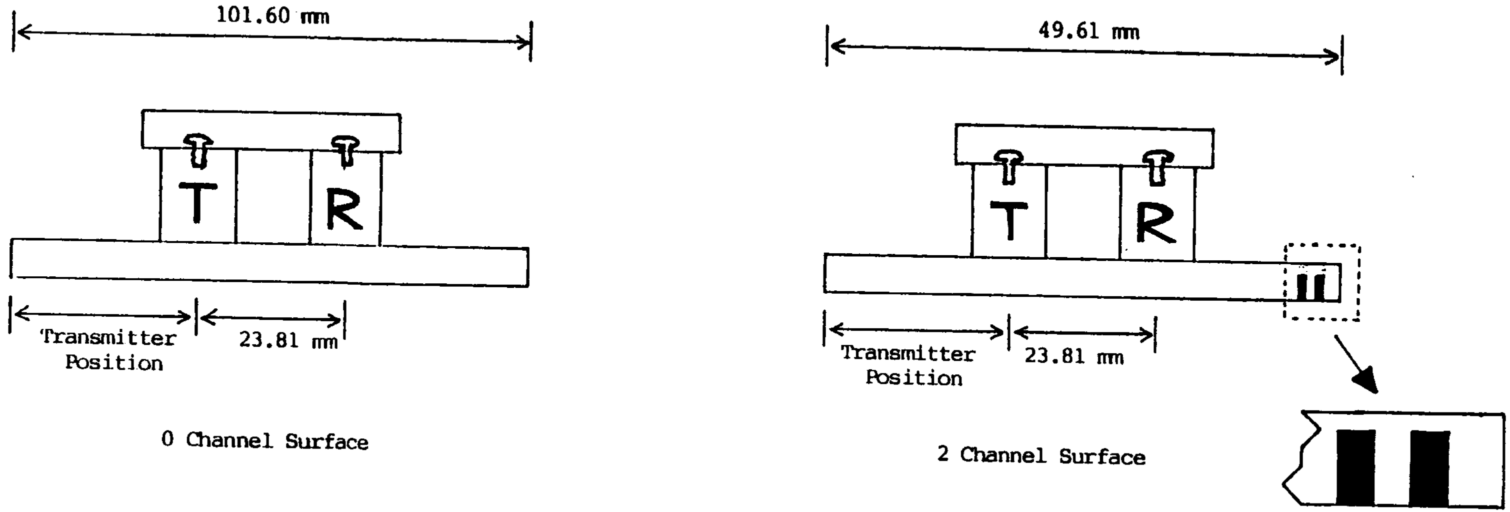

FIGURE 16: EXPERIMENTAL SETUP TO DETERMINE EMAT CHANNEL RESOLUTION CAPABILITY

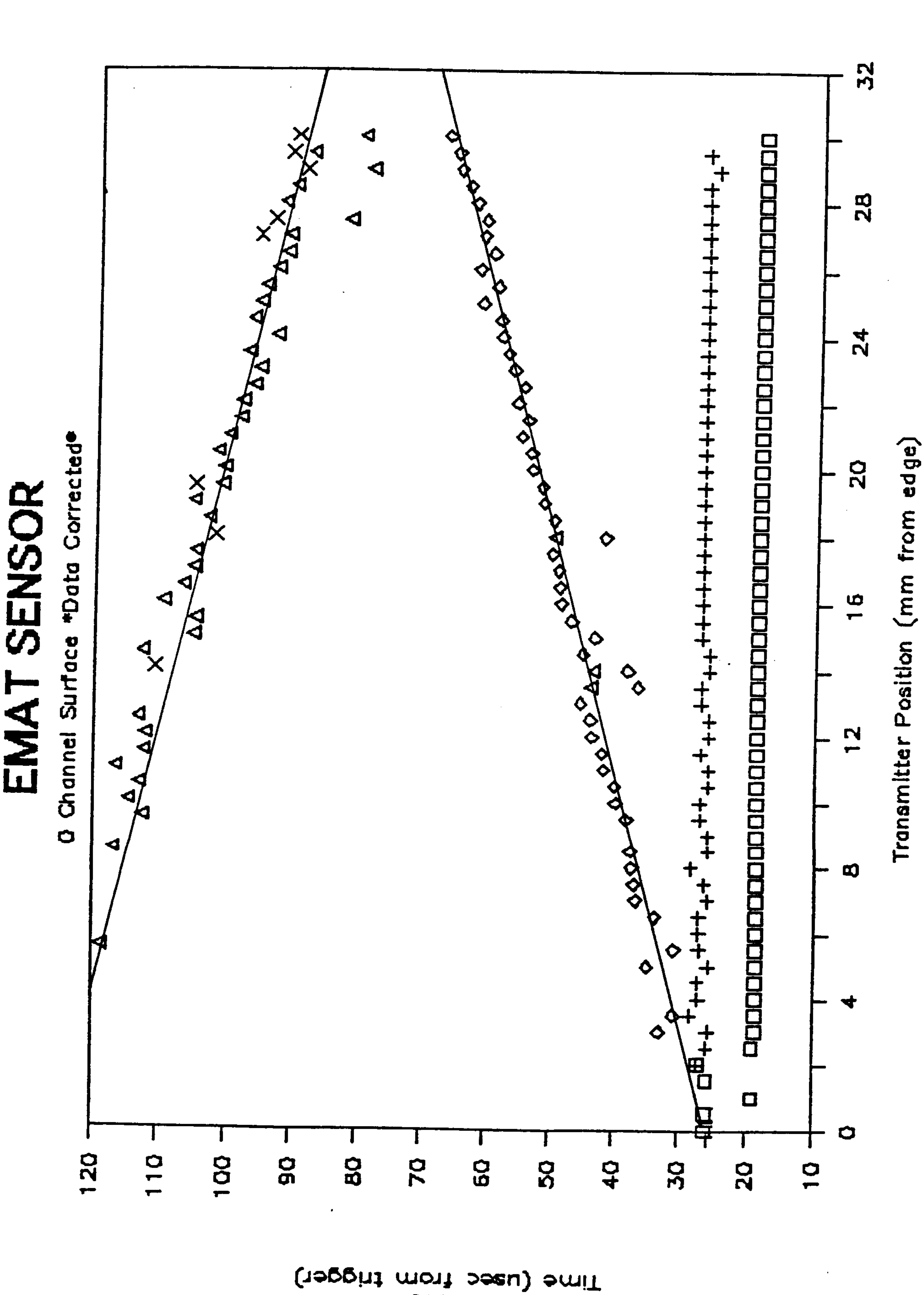
EMAT SENSOR
◇ Channel Surface *Data Corrected*
Time (usec from trigger)
120
110
100
90
80
70
60
50
40
30
20
10
Transmitter Position (mm from edge)
0
4
8
12
16
20
24
28
32

FIGURE 17

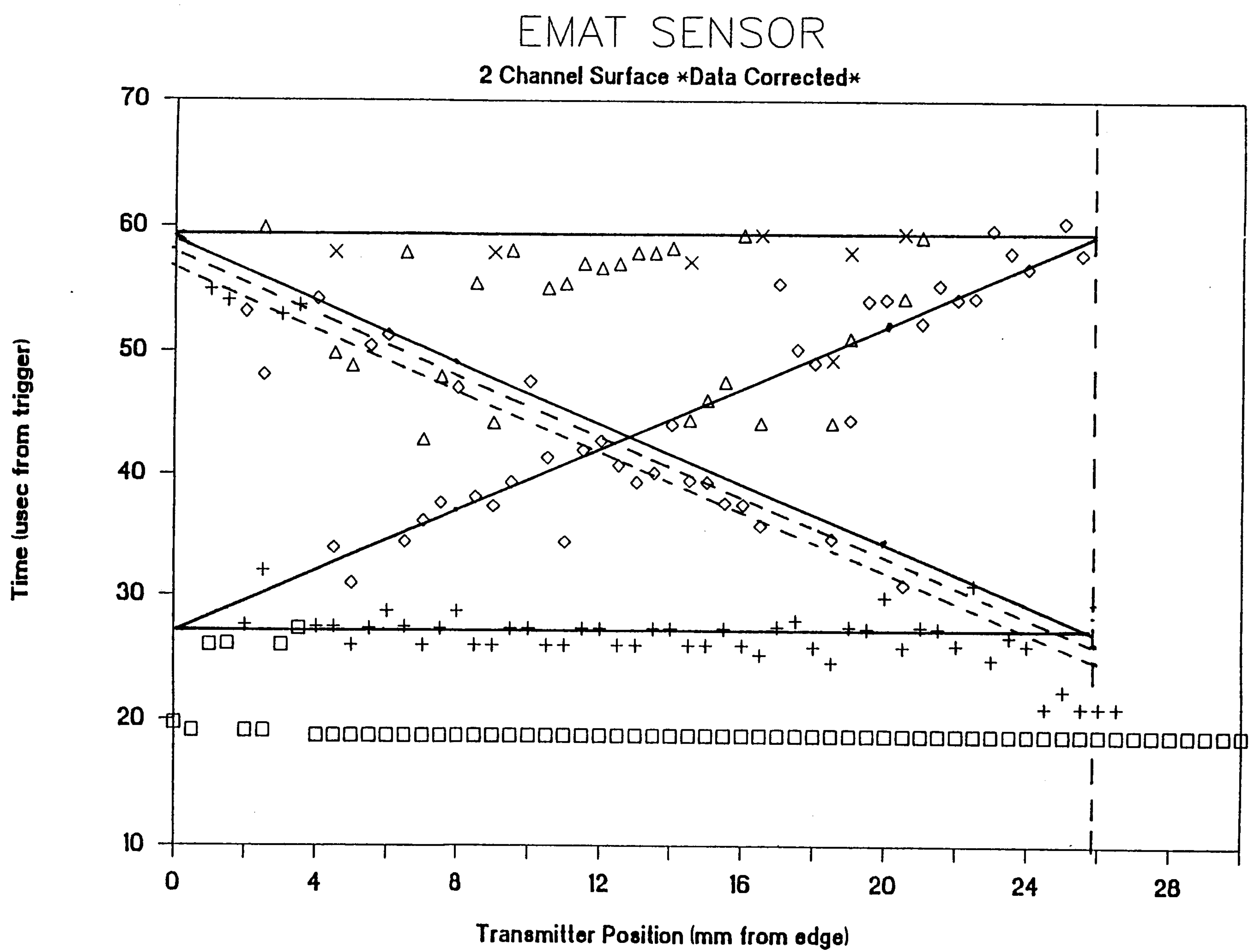
EMAT SENSOR
2 Channel Surface *Data Corrected*
Time (usec from trigger)
70
60
50
40
30
20
10
0
4
8
12
16
20
24
28
Transmitter Position (mm from edge)

FIGURE 18